A measurement of the branching ratios of D^+ and D_s^+ hadronic decays to four-body final states containing a K_S

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(May 16, 2001)

We have studied hadronic four-body decays of D^+ and D_s^+ mesons with a K_S in the final state using data recorded during the 1996-1997 fixed-target run at Fermilab high energy photoproduction experiment FOCUS. We report a new branching ratio measurement of $\Gamma(D^+ \to K_S K^- \pi^+ \pi^+)/\Gamma(D^+ \to K_S \pi^+ \pi^+ \pi^-) = 0.0768 \pm 0.0041 \pm 0.0032$. We make the first observation of three new decay modes with branching ratios $\Gamma(D^+ \to K_S K^+ \pi^+ \pi^-)/\Gamma(D^+ \to K_S \pi^+ \pi^+ \pi^-) = 0.0562 \pm 0.0039 \pm 0.0040$, $\Gamma(D^+ \to K_S K^+ K^- \pi^+)/\Gamma(D^+ \to K_S \pi^+ \pi^+ \pi^-) = 0.0077 \pm 0.0015 \pm 0.0009$, and $\Gamma(D_s^+ \to K_S K^+ \pi^+ \pi^-)/\Gamma(D_s^+ \to K_S K^- \pi^+ \pi^+) = 0.586 \pm 0.052 \pm 0.043$, where in each case the first error is statistical and the second error is systematic.

PACS numbers:13.25.Ft, 14.40.Lb

To understand hadronic decays of a heavy quark system one needs to address final state interactions. These become more complicated as the number of final state hadrons increase, since the signatures of the weak decay of the heavy quark are masked by the hadronic degrees of freedom. Theoretical predictions are still limited to two-body decays, which have been analyzed extensively in the theoretical literature [1–3]. For example, Bauer, Stech and Wirbel [4] have used a factorization approach. Bedaque, Das, and Mathur [5] and Kamal, Verma and Sinha [6] have used heavy quark effective theory. Much less is known about four-body hadronic decays than about two or three-body decays. More experimental data on higher multiplicity modes is essential to improving our understanding of the decay process in heavy quark systems. In this letter we report on D^+ and D_s^+ branching ratios into four-body final states involving a K_S. We measure the D^+ decay rates into $K_S K^- \pi^+ \pi^+$,

$K_SK^+\pi^+\pi^-$, and $K_SK^+K^-\pi^+$ relative to $K_S\pi^+\pi^+\pi^-$ and the decay rate of $D_s^+ \rightarrow K_SK^+\pi^+\pi^-$ relative to $D_s^+ \rightarrow K_SK^-\pi^+\pi^+$ (throughout this letter the charge conjugate state is implied). Among these final states only the $K_SK^-\pi^+\pi^+$ final state has been observed previously [7]. These final states have several interesting resonant contributions which will be the subject of a future report.

We collected the data for this study during the 1996-1997 fixed-target run of the photoproduction experiment, FOCUS at Fermilab. This experiment utilized a forward multi-particle spectrometer to study charmed particles produced by interactions of high energy photons, $\langle E_\gamma \rangle \approx 180$ GeV, with a segmented BeO target. Charged particles were traced by silicon microstrip vertex detectors. These detectors provide excellent separation between the reconstructed production and decay vertices. The vertex resolution is approximately 6 μm in the transverse direction and 300 μm in the longitudinal direction. Three multi-cell threshold Čerenkov detectors were used to identify charged hadrons.

We reconstructed the K_S candidates using the decay $K_S \rightarrow \pi^+\pi^-$ and calculated the error on the K_S mass for each candidate. We required the K_S mass be within 3σ of the nominal K_S mass which rejects nearly all of the e^+e^- pair background. To reduce the $\Lambda^0 \rightarrow p\pi^-$ background we applied a Čerenkov particle identification cut of 5 units on the difference in the log likelihoods between the pion and proton hypothesis [8] on the K_S daughter track with higher momentum.

We selected the final states using a candidate driven vertexing algorithm [9]. A secondary vertex was formed from the reconstructed tracks and the momentum vector of the charm candidate was used as a *seed* track in finding the primary vertex in the event. We required that the primary and secondary vertices be formed with a confidence level greater than 1%. The significance of separation between the primary and secondary vertex is called ℓ/σ_ℓ. We required $\ell/\sigma_\ell > 9$ for D^+ candidates and $\ell/\sigma_\ell > 7$ for D_s^+ candidates. We also required the proper decay time be less than 5 times the candidate particle's lifetime [10]. The vertexing algorithm provides two estimators of the relative isolation of the vertices. The *primary vertex isolation* (ISO1) estimator is the confidence level of the hypothesis that a track in the secondary vertex was also in the primary vertex; the *secondary vertex isolation* (ISO2) is the confidence level that another track originates from the secondary vertex. We required ISO1 be less than 1% and ISO2 less than 0.1%. For the $D^+ \rightarrow K_SK^-\pi^+\pi^+$ decay mode, this removes 80% of the background and retains 70% of the signal. Further, we required that the decay vertices be out of target material, eliminating backgrounds from interactions which are induced by particles from the primary interaction or from conversions of spurious photons.

In addition to the vertexing requirements, we used Čerenkov particle identification cuts. For the charged kaon candidates we required the kaon hypothesis be favored over the pion hypothesis by 2 units of likelihood (for the $D^+ \rightarrow K_SK^+K^-\pi^+$, we required 2 units for the faster kaon but only 1 unit for the slower kaon).

Finally, the charm candidates were required to have a momentum greater than 30 GeV/c, which removed combinatoric non-charm backgrounds. For all decay modes we selected cuts by maximizing the figure of merit defined as $\mathcal{N}^2_{\rm signal}/(\mathcal{N}_{\rm signal} + \mathcal{N}_{\rm background})$, as well as minimizing reflection background.

We investigated several possibilities for contamination of either signal region due to reflections from partly reconstructed charmed particles. We find no evidence in the data for an enhancement due to $\Lambda_c^+ \rightarrow K_Sp\pi^+\pi^-$ where the p is misidentified as a K or due to $\Lambda_c^+ \rightarrow \Lambda^0\pi^+\pi^+\pi^-$ where the Λ^0 is misidentified as a K_S. We also investigated contamination of the $D_s^+ \rightarrow K_SK^-\pi^+\pi^+$ and $D_s^+ \rightarrow K_SK^+\pi^+\pi^-$ signal region due to π/K misidentification of the decay $D^+ \rightarrow K_S\pi^+\pi^+\pi^-$. This reflection is incorporated in the fit (see Figs. 1 and 2). Double misidentification between the $K_SK^-\pi^+\pi^+$ and $K_SK^+\pi^+\pi^-$ decay modes was found to be negligible.

In order to minimize systematic effects we chose normalization channels which have similar topologies to the signal modes, and we applied the same vertex requirements. Fig. 1 shows the invariant mass distributions using the D^+ selection cuts and Fig. 2 shows the invariant mass distributions using the D_s^+ selection cuts. We parameterized the signal with a Gaussian and the background with a quadratic polynomial plus a reflection shape. For the $D^+ \rightarrow K_S\pi^+\pi^+\pi^-$ normalization mode we used a linear background. The reflections in Figs. 1(a), 1(b) and Figs. 2(a), 2(b) from $D^+ \rightarrow K_S\pi^+\pi^+\pi^-$ and Fig. 1(c) from $D^+ \rightarrow K_SK^-\pi^+\pi^+(K_SK^+\pi^+\pi^-)$ occur due to the misidentification of a π as a K. The shapes were determined by Monte Carlo simulations and the reflection amplitudes are free parameters in the fit.

The final states in this study have resonant substructure in their decay modes which may affect the reconstruction efficiency. We generated a Monte Carlo for each final state using an incoherent mix of various subresonant decay modes and a non-resonant contribution. For the decay $D^+ \rightarrow K_S\pi^+\pi^+\pi^-$ we used its known subdecay modes to determine the efficiency. Mini-Monte Carlo studies showed this efficiency is consistent with that of allowing interferences between the states. For the other decay modes, where little is known about the resonant substructure, we determined the efficiencies based on which sub-decay we found to be dominant. The decay mode used for the $K_SK^-\pi^+\pi^+$ ($K_SK^+K^-\pi^+$) final state was $\overline{K}^{*0}K^{*+}$ ($K_S\phi\pi^+$). The $K_SK^+\pi^+\pi^-$ final state has contributions from many sub-decay modes;

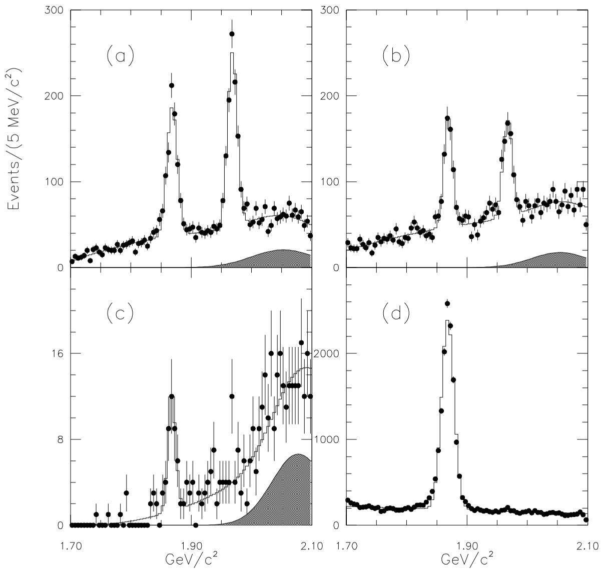

FIG. 1. The invariant mass distributions with D^+ selection cuts. (a) shows the final state $K_S K^- \pi^+ \pi^+$, (b) $K_S K^+ \pi^+ \pi^-$, (c) $K_S K^+ K^- \pi^+$ and (d) $K_S \pi^+ \pi^+ \pi^-$. The data are indicated by points with error bars and the solid line is the fit. The shaded regions are charm reflection backgrounds.

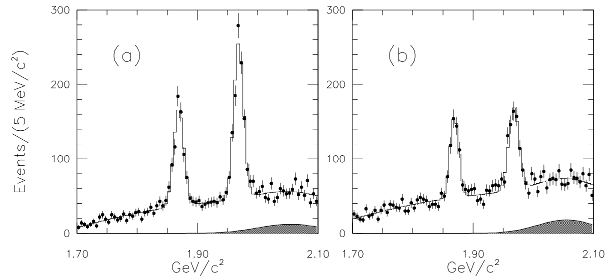

FIG. 2. The invariant mass distribution with D_s^+ selection cuts. (a) shows the final state $K_S K^- \pi^+ \pi^+$ and (b) $K_S K^+ \pi^+ \pi^-$. The data are indicated by points with error bars and the solid line is the fit. The shaded regions are charm reflection backgrounds.

Decay Mode	$\mathcal{N}_{\text{signal}}$	Γ_{rel}
$D^+ \to K_S K^- \pi^+ \pi^+$	670 ±35	0.0768±0.0041±0.0032
$D^+ \to K_S K^+ \pi^+ \pi^-$	469 ±32	0.0562±0.0039±0.0040
$D^+ \to K_S K^+ K^- \pi^+$	35 ±7	0.0077±0.0015±0.0009
$D^+ \to K_S \pi^+ \pi^+ \pi^-$	11590±121	1
$D_s^+ \to K_S K^+ \pi^+ \pi^-$	476 ±36	0.586±0.052±0.043
$D_s^+ \to K_S K^- \pi^+ \pi^+$	837 ±38	1

TABLE I. Measured branching ratios. Γ_{rel} is the branching ratio relative to $D^+ \to K_S \pi^+ \pi^+ \pi^-$ for the D^+ modes and $D_s^+ \to K_S K^- \pi^+ \pi^+$ for the D_s^+ modes. The errors on the branching ratios are statistical and systematic, respectively.

therefore we assumed a non-resonant substructure to obtain the efficiency for this final state. With these Monte Carlo efficiencies, we measured the relative branching ratios which are summarized in Table I. For each of the signal modes we also obtained efficiencies with different resonant and non-resonant substructure combinations. We used the spread of the various resonant and non-resonant efficiencies to determine the systematic error on the efficiency calculation for each state. We estimated the relative uncertainties in efficiencies due to uncertainties in the branching fractions into resonant sub-states to be 3.9% for $D^+ \to K_S K^- \pi^+ \pi^+$, 6.7% for $D^+ \to K_S K^+ \pi^+ \pi^-$, 9.8% for $D^+ \to K_S K^+ K^- \pi^+$, 4.6% for $D_s^+ \to K_S K^- \pi^+ \pi^+$, and 4.6% for $D_s^+ \to K_S K^+ \pi^+ \pi^-$.

A study of the stability and behavior for each branching ratio was performed using variations of our analysis cuts; we found no bias from the choice of analysis cuts. Further, we split our data into independent subsamples based on D momentum and the different run periods in which the data were accumulated. This technique is described in detail in reference [11]. We found no systematic uncertainties from splitting our data.

The systematic uncertainty for each branching ratio includes efficiency dependencies from sub-resonant states and from variation of the fit parameters (mostly due to background parameterization variation).

To conclude, we have improved the previous measurements of the $D^+ \to K_S K^- \pi^+ \pi^+$ branching ratio and have made the first observation of the $D^+(D_s^+) \to K_S K^+ \pi^+ \pi^-$ and $D^+ \to K_S K^+ K^- \pi^+$ decay processes using a high statistics sample of photoproduced charmed particles from the FOCUS experiment at Fermilab.

We wish to acknowledge the assistance of the staffs of Fermilab and the INFN of Italy, and the physics departments of the collaborating institutions. This research was supported in part by the U. S. National Science Foundation, the U. S. Department of Energy, the Italian Istituto Nazionale di Fisica Nucleare and Ministero dell'Università e della Ricerca Scientifica e Tecnologica, the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico, CONACyT-México, the Korean Ministry of Education, and the Korean Science and Engineering Foundation.

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